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Working Memory in Children: A Time-Constrained Functioning Similar to Adults

Sophie Portrat*,

Valérie Camos**,

Pierre Barrouillet***

** Université de Bourgogne*

*** Université de Bourgogne & Institut Universitaire de France*

**** Université de Genève*

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Corresponding author:

Sophie Portrat

Université de Bourgogne

L.E.A.D. - C.N.R.S. UMR 5022

Pôle AAFE, Esplanade Erasme

BP 26513

21065 DIJON Cedex

FRANCE

Email : Sophie.Portrat@u-bourgogne.fr

Tel: +33 (0) 3 80 39 36 88

Fax: +33 (0) 3 80 39 57 67

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Abstract (150 words)

Within the Time-Based Resource-Sharing (TBRS) model, we tested a new conception of the relationships between processing and storage in which the core mechanisms of WM are time constrained. However, our previous studies were restricted to adults. The present study aimed at demonstrating that these mechanisms are present and functional before adulthood. For this purpose, we investigated the effect on maintenance of the duration of the attentional capture induced by processing. In two experiments using computer-paced WM span tasks, 10-year-old children were asked to maintain letters while performing spatial location judgments. The duration of this processing was manipulated by varying either the discriminability between target locations or the contrast between targets and background. In both experiments, as we previously observed in adults, longer processing times resulted in poorer recall. These findings suggest that the core mechanisms of WM described by the TBRS model are already settled in childhood.

Key words: Working memory; attention; time decay; cognitive development; children; response selection.

Working Memory (WM) is a capacity-limited cognitive system devoted to the simultaneous maintenance and processing of information that plays a crucial role in complex as well as in many elementary cognitive activities (Barrouillet, Lépine, & Camos, 2008; Camos, 2008; Camos & Barrouillet, 2004; Kyllonen & Christal, 1990). It has often been argued that most of the differences in cognition between children and adults are due to children's limitations in WM capacity (Case, 1985; Halford, 1993; Pascual-Leone, 1970). We have recently proposed a new model of WM named the Time-Based Resource-Sharing (TBRS) model that puts forward a new conception of the relationships between processing and storage in which the core mechanisms are time constrained (Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2007). We verified the main assumptions of this model in adults (Barrouillet et al., 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007), but it remains undecided if WM functioning presents the same characteristics and constraints in children. Thus, the present study addressed this question by testing in children the specific predictions of our model concerning the effect of time on WM.

The TBRS model is based on four main proposals. First, the two main functions of WM that are processing and maintenance of information rely on the same limited attentional resource. Second, a bottleneck constrains central processes allowing only one attention demanding cognitive step to take place at a time. This sequential functioning of WM means that when attention is occupied by some processing episode, it is not available for the maintenance of memory items. Third, as soon as attention is switched away from maintenance to processing, the activation of the memory items suffers from a time-related decay and their memory traces fade away. A refreshment of these items is thus needed before their complete disappearance through reactivation by attentional focusing. Fourth, this sharing of attention is achieved through a rapid and incessant switching of attention from processing to maintenance occurring during short pauses that would be freed while concurrent processing is running.

Following these assumptions, when the time allowed to perform the processing component of a WM span task is kept constant, any increase in the duration of the attentional capture this processing involves extends the period during which memory traces fade away, thus resulting in a greater memory loss. This model leads to a new metric of the cognitive load involved by a given task as the proportion of time during which this task occupies attention.

To test these assumptions, we elaborated a new paradigm of computer-paced WM tasks that permits a careful control of time parameters. In these tasks, participants are presented with items to be recalled, for example letters. After each letter, they have to perform an intervening task divided in atomic steps, the duration of this task being controlled. In many experiments, we demonstrated that any increase in the cognitive load induced by this intervening task has a detrimental effect on concurrent maintenance and recall. For example, increasing the number of atomic steps such as reading digits within a fixed time interval or reducing the time allowed to perform a fixed number of processing steps resulted in poorer recall (Barrouillet et al., 2004). The most striking test of the TBRS model was to verify that a mere increase in the duration of each atomic processing step results in a memory loss, even if their number and nature as well as the total time allowed to perform them is kept constant. For this purpose, Barrouillet et al. (2007) used a task in which each letter was followed by eight stimuli consisting in a black square centered on one of two possible locations either in the upper or lower part of the screen. Adult participants were asked to judge the location of each square as fast as possible by pressing appropriate keys. According to the TBRS model, longer response selections should be more disruptive on concurrent maintenance of information because they involve a longer occupation of the central bottleneck impeding other attentional demanding processes such as refreshment activities to take place. We manipulated the duration of the response selections by varying the distance between the two possible locations (either 5 mm or 68 mm apart). As we surmised, the close condition drastically diminished the

targets discriminability and induced longer responses than the distant condition (377 ms and 314 ms, respectively). As the TBRS model predicted, the longer attentional capture induced by the close condition had a detrimental effect on maintenance and resulted in poorer recall performance than the distant condition (mean spans of 5.51 vs. 5.81, respectively). This finding led strong support to the TBRS model by suggesting that longer processing episodes involve longer attentional capture impeding the switching toward decaying memory traces and their refreshment.

However, Towse and Hitch (2006) cogently noted that the findings supporting the TBRS model are restricted to adults and that it is not clear that our interpretation would necessarily apply to children. We must admit that this remark is quite sound. Although we have studied children's WM, we never specifically tested in children the central assumption of the TBRS model concerning time-related effects. Barrouillet and Camos (2001) observed in 9- and 11-year-old children that increasing the difficulty of the processing component while keeping constant the time allowed to perform it resulted in lower WM span, but they did not address the precise mechanism underlying this trade-off. Gavens and Barrouillet (2004) extended these results by demonstrating that increasing the attentional demand of the processing resulted in lower span in 8- and 10-year-old children, but their work did not explore the specific effect of time on storage.

Even if the TBRS does not claim that children and adults must be alike, the model assumes that the core mechanisms of WM should be functional before adulthood. It is known that refreshing mechanisms such as articulatory rehearsal are not used before 7 (Henry & Millar, 1993), and it is probably the same for the attentional refreshment hypothesized by the TBRS model. For example, simple span tasks constitute a reliable measure of WM in young children, suggesting that they do not use any strategy or refreshing mechanism to maintain information active (Cowan et al., 2005). We recently obtained evidence that WM spans in

children below 7 are not affected by variations of the cognitive load involved by concurrent processing, indicating that the attentional refreshing mechanism is not yet efficient (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, under revision). However, at least from 7 years onward, we assume that the core mechanisms of WM should be functional and that the same factors should constrain adults' and children's WM. This conception is at odds with Towse and Hitch's (1995; Hitch, Towse, & Hutton, 2001) model of WM in children. These authors assume that, in complex WM span tasks, there is no attempt to actively maintain the memory traces during processing and no attentional refreshing mechanism. Thus, recall performance does not depend on the cognitive load of the intervening task but merely on the delay of retention during which memory traces suffer from a time-related decay.

In the following experiments, we tested in 10-year-old children the pivotal prediction that any increase in the duration of the attentional capture involved by each step of the processing component of a WM span task results in a decrease in recall performance, although the total delay of retention during which memory decay could occur is kept constant. Experiment 1 aimed at replicating in children Barrouillet et al.'s (2007) finding reported above. Experiment 2 extended this result by introducing a new manipulation of the duration of the processing component of the task.

Experiment 1

This experiment aimed at replicating Barrouillet et al.'s (2007) Experiment 2 in which adults were asked to remember letters while performing series of response selections by judging the location of squares presented either on the upper or lower part of the screen. The duration of each response selection was manipulated by varying the discriminability of the two possible locations on which the squares appeared. Here, 10-year-old children were presented with the same task. The TBRS model predicts that longer response selections should result in poorer recall performance.

Method

Participants

Twenty-four French fifth graders (15 girls and 9 boys; mean age = 10; 5 years; SD = 4 months) from primary schools in Dijon (France) participated as volunteers.

Material and procedure

The material, the procedure and the temporal characteristics of the tasks were the same as in Barrouillet et al.'s (2007) Experiment 2 except for the lengths of the to-be-remembered series of letters that were reduced to be adapted to children's capacities. Children were seated about 60 cm from the laptop screen and were presented with series of 1 to 5 consonants to be remembered. Each consonant was followed by a series of 8 stimuli successively displayed on screen. These stimuli consisted in a black square (side = 18 mm subtending 2 degrees in visual angle) centered on one of two possible locations either in the upper or the lower part of the screen. In the *distant* condition, the two locations were 68 mm apart (6.5 degrees in visual angle), whereas in the *close* condition, this distance was reduced to 5 mm (0.5 degrees in visual angle), thus creating a 13 mm overlap between the two targets. For each length, 3 series of consonants were associated with each condition of discriminability of the location judgment task, resulting in a total of 30 series of consonants to be remembered that were presented to each participant according to two fixed random orders of presentation.

Each series began by a first screen indicating the condition and the number of letters to be remembered (e.g., "Close squares / 3 Letters"). After a 500 ms white screen, a ready signal (an asterisk) centered on screen for 750 ms was followed by a 500 ms delay. Then, the first letter succeeded for 1500 ms. After a post-letter delay of 500 ms, each of the 8 squares of the location judgment task appeared for 667 ms and was followed by a 333 ms delay, resulting in a total of 1 s per stimulus. The following consonant then appeared for 1500 ms followed by the eight ensuing squares, and so on. At the end of each series, the word "Rappel" (recall) was

displayed on screen. In each condition and each series, squares were randomly displayed in the upper and the lower locations with the same frequency. Children were asked to read aloud each letter when appeared, to judge the location of each square as fast as possible without sacrificing accuracy by pressing either a left- or a right-handed key for the lower and the upper location, respectively, and then to write down the remembered letters in correct order by filling out frames containing the appropriate number of boxes. Recall performance was computed as WM span scores in which each correctly recalled series counted as a third. The total number of thirds was added up to provide a span score (Barrouillet & al., 2004). For example, the correct recall of all of the series of one, and two letters, and of one series of three letters resulted in a span of $(3 + 3 + 1) \times 1/3 = 2.33$. Response time and accuracy during the location judgment task were also recorded.

A training phase familiarized participants with the location judgment task with 104 stimuli in each experimental condition. Children heard a beep if they made a mistake or they were too long to respond (i.e. more than 1 s). If they didn't reach 80 % of correct responses, they were asked to perform again the same series of squares with a maximum of 3 training phases. Before the experimental session itself, they performed the WM task with three series of letters and stimuli to be processed ("close squares / 1 letter", "distant squares / 3 letters", and "close squares / 2 letters").

Results and discussion

All of the children reached the 80% criterion during the training phase and took part in the experimental session. As we anticipated, the close condition elicited longer response times than the distant condition (488 ms, $SD = 36$, and 431 ms, $SD = 51$, respectively), $t(23) = 7.83$, $d = 1.27$, $p < .001$, and also more errors (66 %, $SD = 9$, and 89 %, $SD = 10$ of correct response, respectively), $t(23) = 12.47$, $d = 2.57$, $p < .001$. As we predicted, these longer processing times had a disruptive effect on recall. The close condition resulted in poorer WM

span than the distant condition (2.86, $SD = 0.65$, and 3.39, $SD = 0.75$, respectively), $t(23) = 3.88$, $d = .75$, $p < .001$.

Thus, this experiment extended to children the findings previously observed in adults. As in adults, decreasing target discriminability induced longer response times and resulted in lower recall performance. As predicted by the TBRS model, the increase in the duration of the attentional capture involved by the close condition had a detrimental effect on concurrent maintenance of verbal information. The fact that this close condition also elicited a higher rate of errors does not question this conclusion. More errors in the close condition could only reflect less attention paid to the intervening task and thus more attention available to maintain memory items, a trade-off that would run counter our hypothesis.

Experiment 2

To strengthen the previous results, we tested the same hypothesis of a time-related effect on maintenance using another experimental manipulation inspired from Liefvooghe, Barrouillet, Vandierendonck, and Camos (2008). In this latter study, adults were asked to perform either parity or magnitude judgment on series of digits presented sequentially during each interletter interval. In one condition, the duration of these judgments was increased by a stimulus degradation through the addition of a visual noise to the digits displayed on screen. In line with studies suggesting that stimulus degradation put special demands on attention (e.g., Heitz & Engle, 2007; Lu & Doshier, 1998), this stimulus degradation should lengthen the capture of attention involved in recognizing and processing each digit and thus should have a damaging effect on concurrent maintenance. As we predicted, the longer response times induced by this degradation yielded lower recall performance.

Similarly, in the present experiment, the response times of the location judgment task used in Experiment 1 were increased by presenting visually degraded squares. For this purpose, the distant condition was presented either with normal or degraded stimuli. As in

Experiment 1, we predicted that the condition inducing longer processing times should result in lower spans.

Method

Participants.

Twenty-eight French fifth graders (17 girls and 11 boys; mean age = 10; 8 years; $SD = 3$ months) from primary schools in Dijon (France) participated as volunteers. None of them participated to the previous experiment.

Material and procedure

Except the stimuli to be processed in the concurrent task, material and procedure were the same as in the previous experiment. Children had to maintain series of 1 to 5 letters while performing a location judgment task in which the two possible locations of squares were always 68 mm apart, as in the distant condition of the previous experiment. Squares appeared on a grey background prepared with Microsoft® Powerpoint® 2004 software (luminosity level: 50%). In a *normal* condition, squares appeared in black (luminosity level: 0%), while in the *degraded* condition, they were grey with 1% of luminosity added to the grey background (luminosity level: 51%). Span scores, response time and accuracy in the location judgment task were recorded as in the previous experiment.

Results and discussion

All of the children reached the 80% criterion during the training phase and took part in the experimental session. Our manipulation was successful and response times were longer for degraded than for normal stimuli (502 ms, $SD = 52$, and 431 ms, $SD = 45$, respectively), $t(27) = 9.55$, $d = 1.47$, $p < .001$. Even if the degraded condition was slightly more difficult than the normal condition, children achieved a good rate of correct response in both conditions (87 %, $SD = 7$, and 91 %, $SD = 5$, respectively), $t(27) = 3.58$, $d = .62$, $p < .01$. As we predicted, the condition that elicited the longer processing times resulted in significantly

lower spans (3.30, $SD = .83$, and 3.58, $SD = .72$, for the degraded and normal conditions, respectively), $t(27) = 2.19$, $d = .37$, $p < .05$. As predicted by the TBRS model, the longer attentional capture induced by the visual search of degraded stimuli disrupted concurrent maintenance. Thus, as we observed in Experiment 1, the manipulations that affect adult's WM performance had similar effects in children, and increasing the processing time resulted in a significant memory loss.

General Discussion

In two experiments, we showed that factors that affect WM functioning in adults have a similar impact in children. As we observed in adults, even small increases in the duration of response selections had a disruptive effect on concurrent maintenance and resulted in poorer recall performance. These facts suggest that, at least from the age 10 onwards, WM has the same time-constrained functioning in children as in adults (Barrouillet et al., 2007).

Processing and maintenance share a common supply in a time-based competition. When attention is occupied by processing episodes, it is no longer available to refresh memory traces that inescapably decay through time. Their maintenance requires to switch attention from processing to storage.

Moreover, the size of the effect observed in Experiment 1 suggests that children's suffers from a stronger temporal decay than adults. The 57 ms of additional processing time per stimulus resulted in a reduction of 16% ($d = .75$) in recall performance compared to 5% ($d = .29$) in adults (Exp. 2 in Barrouillet et al., 2007) for approximately the same extra processing time (63 ms). This difference could also be due at least in part to less efficient refreshing mechanisms when attention is available or to a lower capacity to adaptively switch attention from processing to storage. Overall, our results suggest that the developmental changes from childhood to adulthood affect the efficiency of the mechanisms implicated in

processing, storage and their coordination rather than the structure and the core functioning of WM that remain unchanged.

It is worth noting that most of the current models of WM have difficulties in accounting for the present results. The detrimental effect of visuo-spatial processing on verbal maintenance is incompatible with a multi-component view of WM that assumes separate resources for verbal and visuo-spatial domains (e.g., Baddeley, 1986). Furthermore, our findings are at odds with models like Oberauer & Kliegl (2006) assuming that interference phenomenon is the unique source of forgetting in WM. It is actually quite difficult to conceive that representation-based interference could be responsible for the effects we observed. Indeed, it can not be assumed that representations of locations of squares share common features that could overlap with phonological representations of letters. It seems definitely improbable that mere reduction in luminance contrast as in Experiment 2 would increase the level of interference between these representations. Similarly, we can not imagine what kind of process-based interference could occur between judging spatial locations and maintaining letters and could lead to the observed memory loss. The simplest way to account for these phenomena is to assume that processing visuo-spatial information and maintaining phonological material rely on the same general resource, as the TBRS model assumes. Moreover, discarding any interference account leads to assume that there is a time-related decay of memory traces responsible for forgetting in WM, in adults as well as in children.

This time-related forgetting, which is particularly pronounced in children, echoes frequent proposals about the role of WM in children performance and cognitive development. It has often been assumed that the limitation in children's cognitive performance is due to their relative incapacity to maintain a large amount of relevant information while performing concurrent activities. The use of slow algorithmic strategies in arithmetic problem solving increases the probability of forgetting the operands involved and jeopardizes the learning of

operand-answer associations in long term memory (Barrouillet, Mignon, & Thevenot, 2008; Geary, 1993). Releasing the constraint related to a fast decay of memory traces is probably one of the main factors of WM as well as cognitive development, either by a greater efficiency of refreshment mechanisms, a higher ability to control attention allocations between processing and storage, or an endogenous diminution in the speed of decay. Future studies will enlighten the respective role of these different factors.

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